Advances in Crosswell Electromagnetics: Steel Cased Boreholes

Barry A. Kirkendall (kirkendall1@llnl.gov; 925-423-1513)
Phillip E. Harben (harben1@llnl.gov; 925-422-3571)
Lawrence Livermore National Laboratory
P.O. Box 808 L-206
Livermore, CA 94550

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Nearly 400 billion barrels of oil are estimated to remain in US reserves; as a result, new geophysical technologies for assessing the practicality and cost of extended oil recovery are urgently needed. The crosswell electromagnetic (EM) induction technique allows precise, high resolution mapping of the spatial conductivity distribution between fiberglass (i.e. nonconductive) cased boreholes, thus providing high resolution reservoir characterization as well as steam and water flood tracking. Potential conductivity contrasts may occur, for example, between oil sands and water sands, during spatial variability of gas-water contacts, or from loss of steam due to incidental fractures. The predominant amount of casing encountered in the oil patch, however, is carbon steel, which significantly attenuates and disperses the inductive electromagnetic energy due to its surface conductivity. The extension of the crosswell EM technique to single and dual steel cased wells would not only greatly expand this technique, but would allow rapid, efficient, and versatile reservoir characterization in the oil field. As this expansion is contingent on a practical and economical solution of EM induction through carbon steel casing, Lawrence Livermore National Laboratory (LLNL) has recently made significant progress towards this end and is continuing to investigate further this technique.

Wu and Habashy (1994) established a foundation for this study with experimental and modeling results regarding the effect of laboratory steel casing on the electromagnetic signals transmitted through such casing. Although the conductivity, magnetic permeability, and the casing wall thickness all affect the induced EM field, it was found that casing thickness and conductivity of carbon steel do not vary significantly. It is therefore the relative change in the magnetic permeability which most affects the EM energy. Wilt et al. (1995) suggest that the casing effect is localized within the pipe section that includes the sensor and that the effect of the casing can be separated. Recent data acquired by LLNL at a site in Richmond, California quantify the effect of steel casing on induction measurements and demonstrate this effect to be separable, as well as a method of separation. This unique site contains adjacent steel and plastic wells in which frequency soundings demonstrate low spectrum (1.0 - 200 Hz) measurements an effective method of isolating the casing response from the formation response. It is shown that the steel casing effect on the induction coil is highly localized, and limited to a maximum of 0.60 meters above and below the coil. Additionally, operating frequencies are optimized in the single steel case, as well as quantification of the difficulties caused by electrical property spatial variations in steel casing. Concerning the dual steel well scenario, preliminary studies suggest a method to weight the effect of each individual carbon steel well. The presence of dual steel collars is easily mapped, and with prior knowledge of their limited spatial effect, it is shown that the effect can be subtracted from the formation response.

Future steel casing research at LLNL concerns the development of new processing methods to quickly and accurately remove steel casing effects, to investigate and use rapid, more efficient methods of tomographic inversion in the presence of high attenuation and dispersion due to carbon steel, and the increase of model resolution in a complex subsurface such as typically encountered at petroleum fields.

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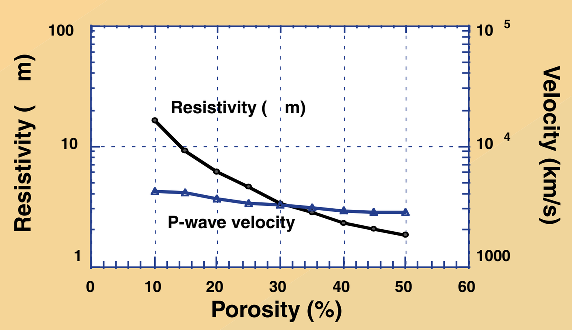
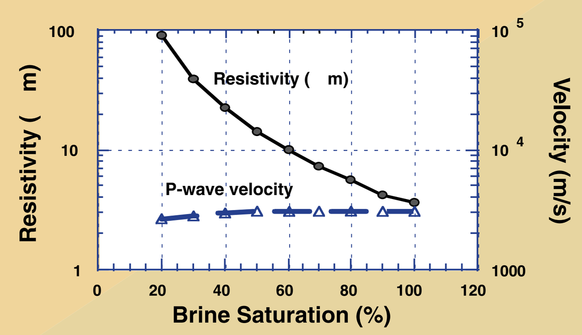
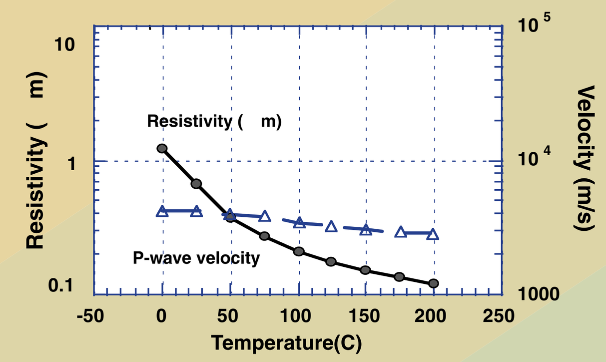
What are the advantages of Electromagnetics?

Electromagnetics can be more sensitive to changes in porosity, temperature, and brine saturation than through the use of seismic methods. This translates into excellent resolving ability for tracking steam floods, water floods, and fracture detection.







New LLNL Crosshole Field System

Receive

- Pentium - based Ethernet / LABVIEW acquisition and operation
- GPIB Instrument control
- Fiber - Optic Voice Communitcation

Logging mast fully extended on the LLNL receiver truck with the rear hydraulic stabilizer system activated. The large fuel capacity allows over 140 hours of operation in remote field sites. The transmitter truck is shown to the far right of the figure at the Richmond Field Station, California - a separation distance of 52 meters.

Transmit

Rear view of the LLNL transmitter truck. The mast is controlled by a hydraulic boom for positioning over boreholes. The site is at the Richmond Field Station, California

- Analog Transmit Coil
- Pentium / LABVIEW based digital acquisition system
- Fiber Optic Ethernet and
- Analog Link with Receive truck
- Transmitter operable up to 125 C
  - 175 C with ne w transmitter

Summary

- Crosswell EM can be used to image through single and dual steel casings
  - An experiment this August at Seneca Resour ces, California, will attempt to better constrain the dual steel casing pr oblem
  - Numerical models of a segmented casing in a layer ed medium are needed to better understand the electrical pr operties of variable pipe sections
- The effect of the steel casing is a linear shift in amplitude and phase which can be subtracted in the frequency domain
- The steel casing effect on the induction coil is limited to 0.60 meters above and below the coil
- To achieve the best balance between formation sensitivity and attenuation, the most effective frequencies for use in induction through steel casing are between 100 Hz and 300 Hz

Future work

Modeling resolution

The necessary resolution is already in the data, the problem is getting it out, since the conductive earth disperses the crosswell signal energy.

— sensitivity analysis

— q-domain wavefield imaging techniques.

Expansion of applications

Crosswell EM through single- and dual-steel casing is clearly the primary focus of this section, although other applications of crosswell EM to be investigated are

— Development of a segmented casing forward modeling code for both vertical and horizontal dipoles in a layer ed medium

— Methods for r emoval of steel casing effects

— Designing a device capable of measuring pr operties of the steel casing

— Measur ement while drilling - the process of placing a transmitting antenna behind the drilling terminus would vastly broaden this technique

— Natural gas field applications which would measur e changes in the water-gas contact .

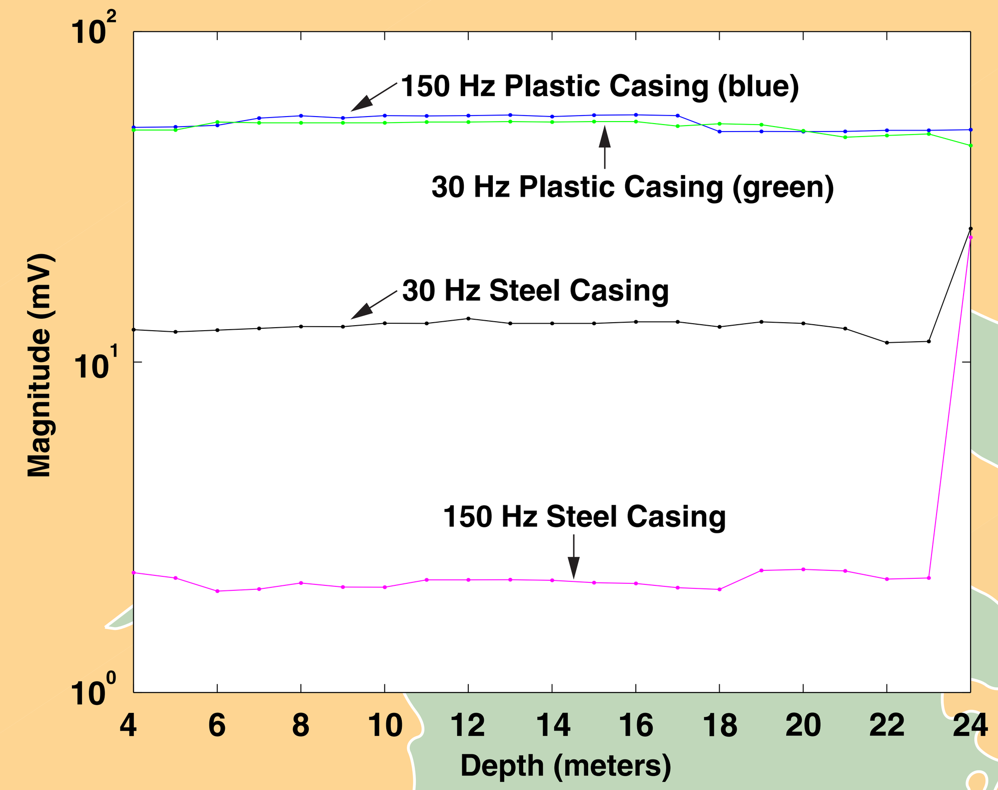
— Using permanent sensors, cemented down-hole

Coupling Data to Reservoir Characteristics and Rock Properties

The LLNL petrophysical laboratory is simultaneously working on several relevant issues regarding the micro effects of steam flooding during enhanced oil recovery processes. These experiments, concerning temperature, conductivity, and pressure, can produce results to help constrain our inversion processes, within steel cased wells.

Figure One

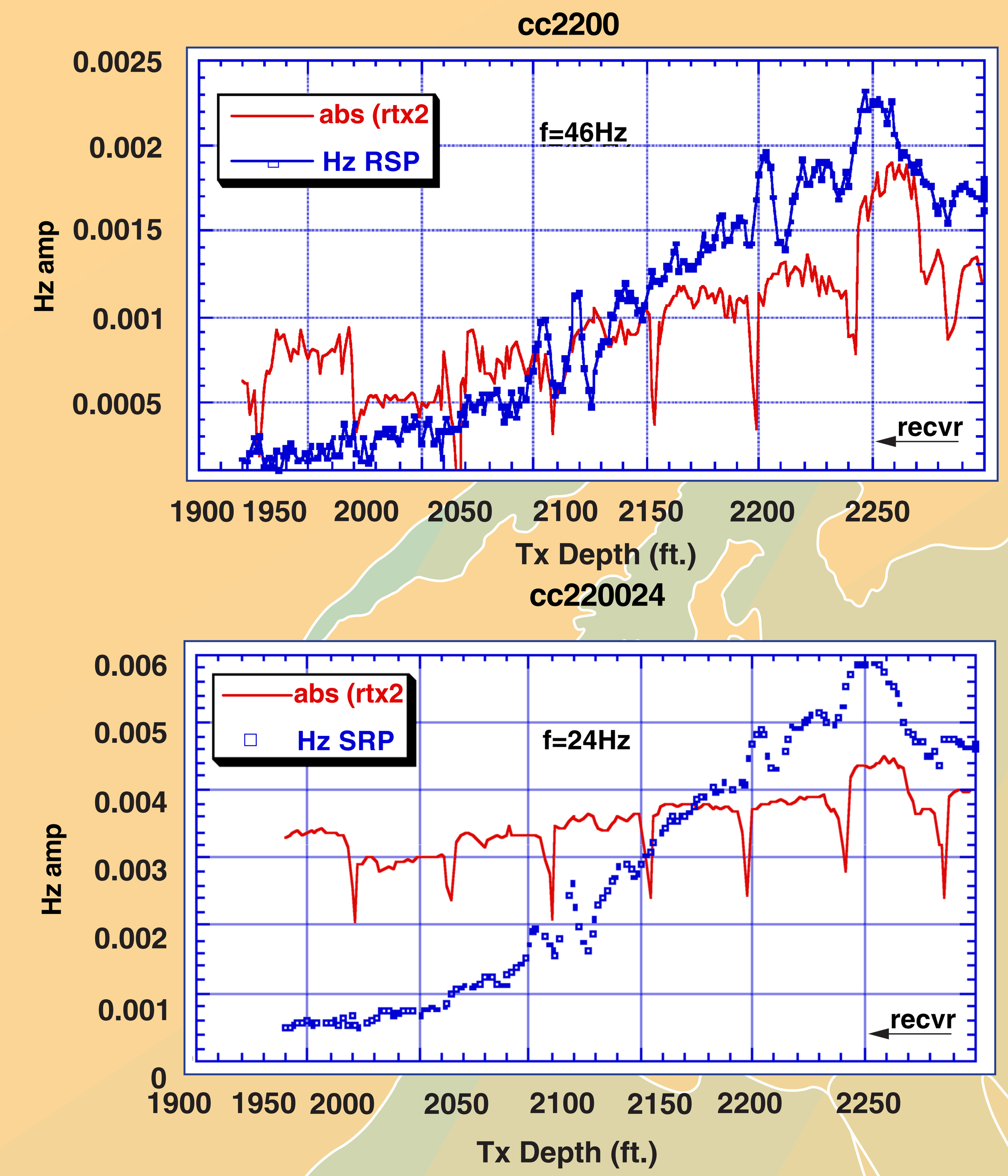
Comparative Amplitude Response of Steel and Plastic Cased Wells



Crosswell magnitude profiles taken at two different frequencies (30 and 150 Hz). Note the abrupt steel cased amplitude jump at 23 meters depth.

Figure Two

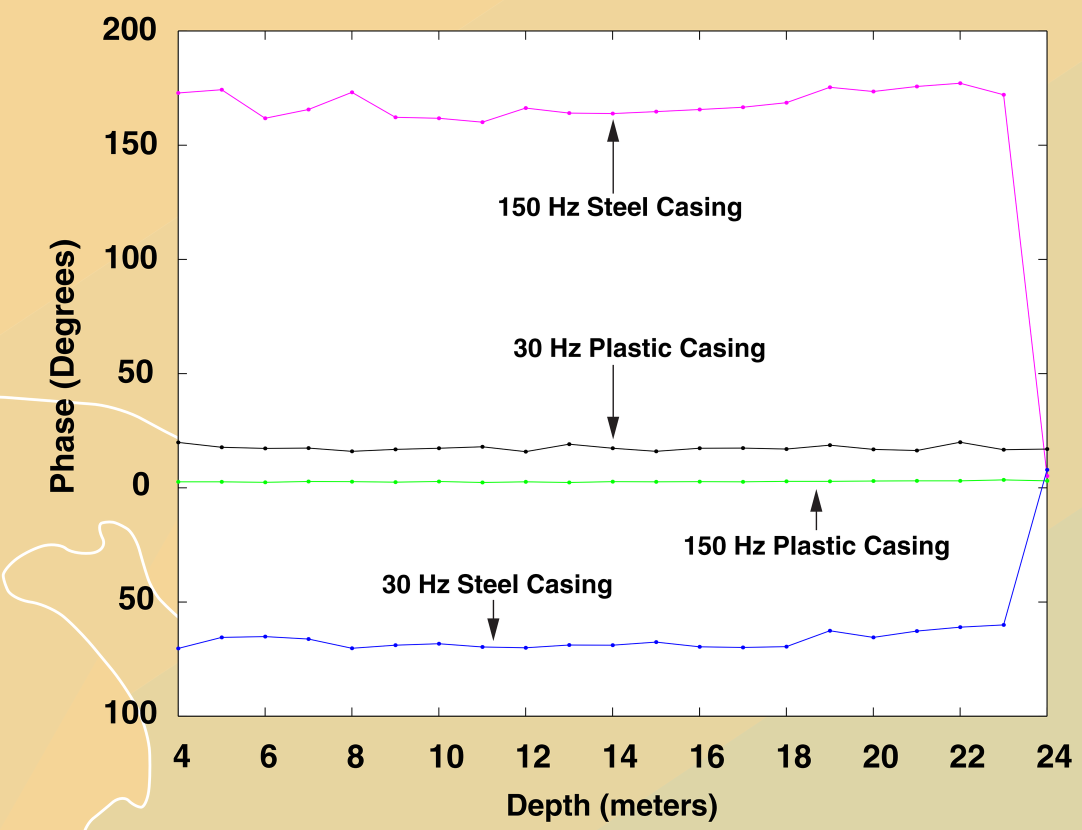
Crosshole EM Data, 2 Steel Casings



Crosswell EM using dual steel casing at two separate frequencies. The red line is the transmitter field, and the blue line represents the field at the receiver. The sharp transmitter field drops are caused by the steel collars, connecting adjacent pipe sections.

Figure Three

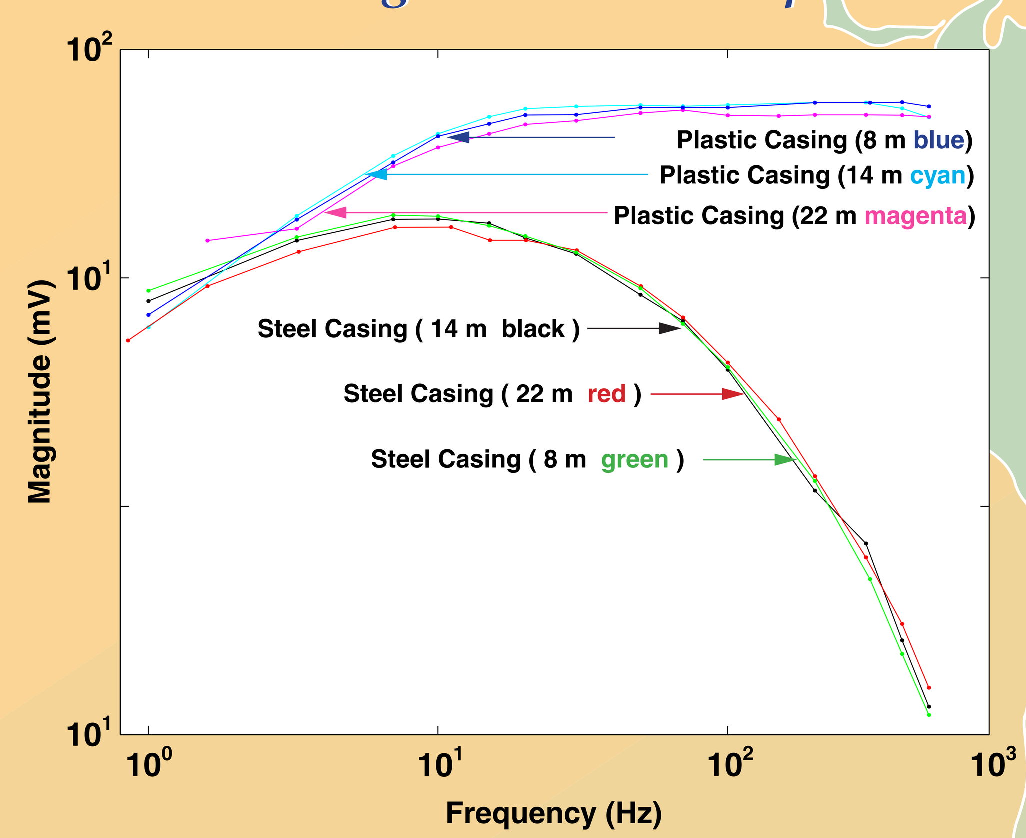
Comparative Phase Response of Steel and Plastic Cased Wells



Crosswell magnitude profiles taken at two different frequencies (30 and 150 Hz). Note the abrupt steel cased phase jump at 23 meters depth.

Figure Four

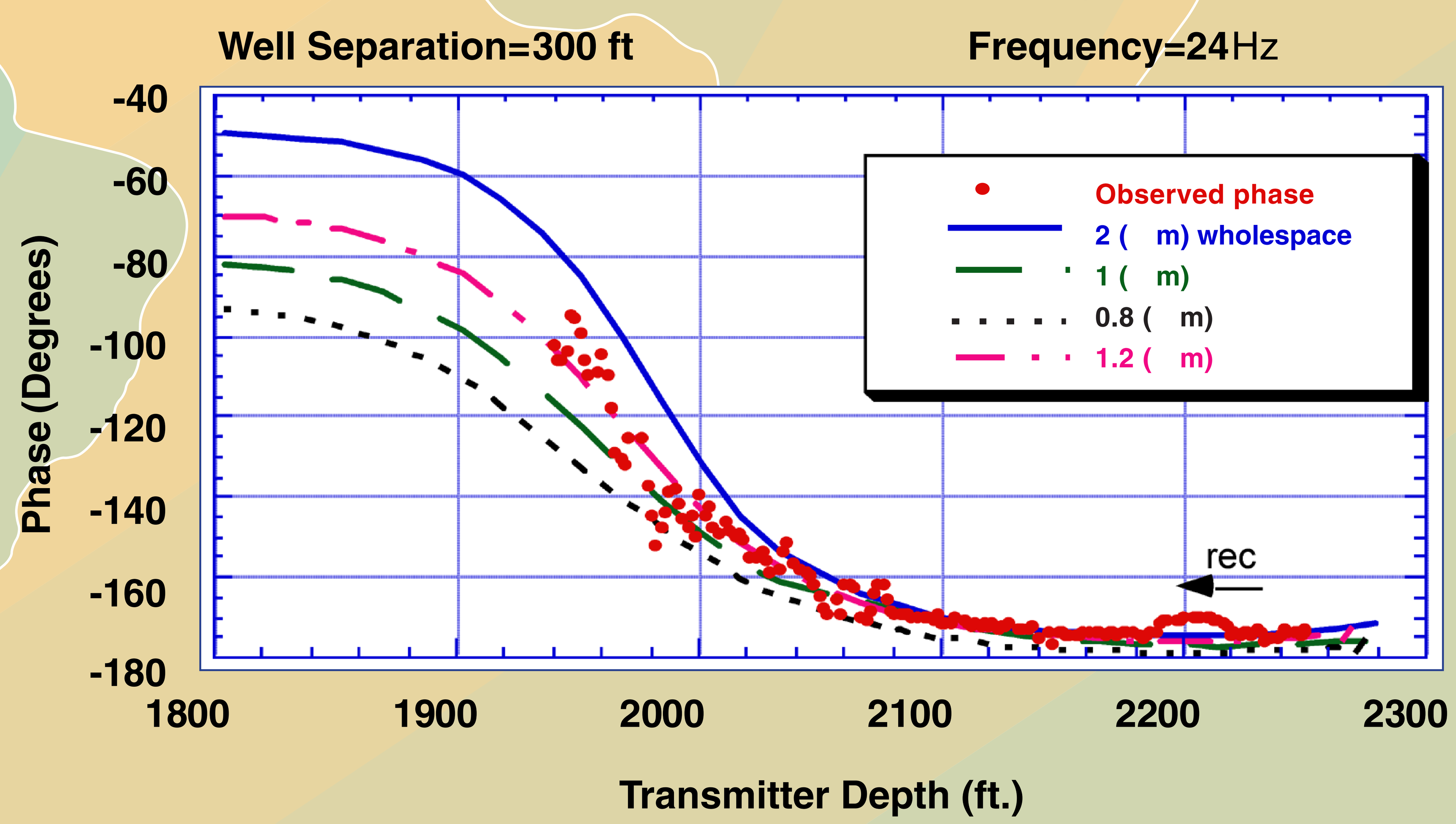
Amplitude Comparison of Frequency soundings at Variable Depth



Receiver amplitude response to transmitter frequency sounding. Variable receiver depth of 8, 14, and 22 meters. Each depth is the center of one continuous steel pipe section of unique electrical properties.

Figure Five

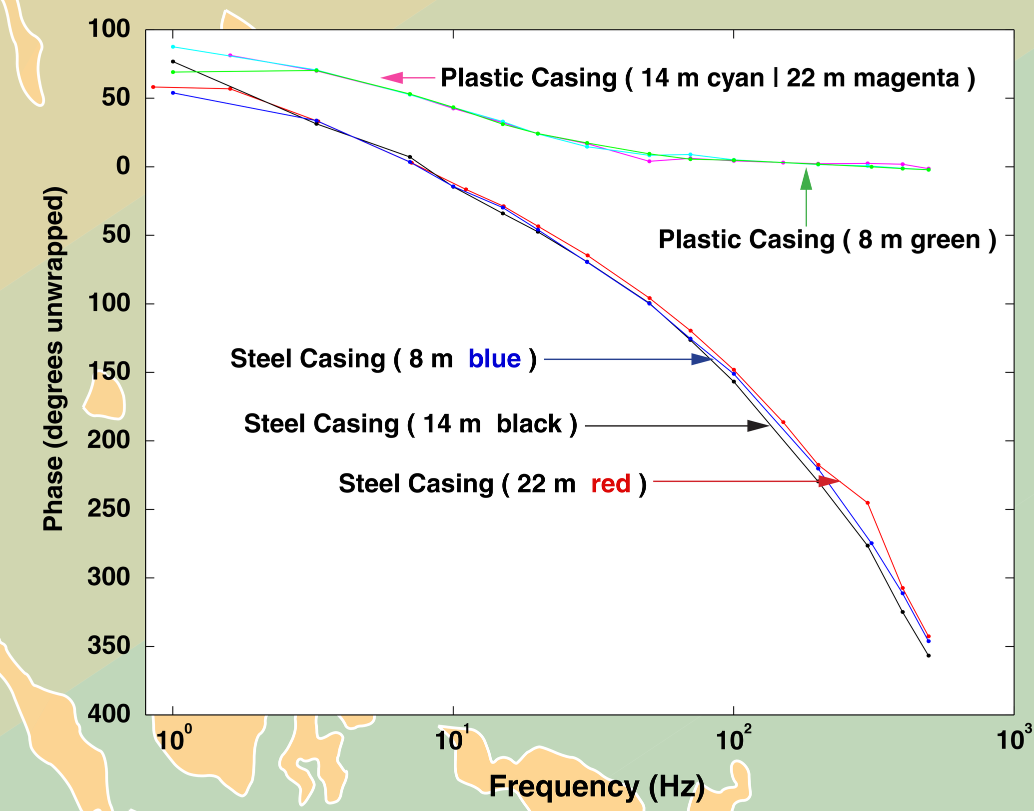
Crosshole EM Phase 2 Steel Casings



Again imaging between dual steel casing; the phase information can be modeled to give an accurate interpretation of the ground conductivity. Modeling such as this suggests that crosswell EM through dual steel casing is feasable.

Figure Six

Phase Comparison of Frequency soundings at Variable Depth



Receiver phase response to transmitter frequency sounding. Variable receiver depth of 8, 14, and 22 meters. Each depth is the center of one continuous steel pipe section of unique electrical properties.

As the steel cased well is open at the hole bottom, the sharp amplitude and phase jump at 23 m as seen in figures 1 and 3, demonstrate that the induction coil is only affected by the casing 0.60 meters above and below the downhole tool. This result is allowing forward and inverse models to be run with more efficient and accurate results.

When conducting crosswell EM surveys within one fiberglass observation well and one steel cased well, the effect of the steel casing is seen as a constant filter, with attenuation dependent on frequency, as shown in figures 4 and 6 The amplitude and phase effects may linearly be subtracted.

Crosswell EM surveys within dual steel casing suffer from high signal attenuation and seen in figures 2 and 5. The major problem, however, with subtracting the dual steel cased wells, is the reletive contribution of each well in the received signal. The solution to this problem suggests knowledge of the electrical properties of the casing. Efforts are currently underway in determining the design of such a tool.